Definition of "Rich Burn Engine" for the Reciprocating Internal Combustion Engine (RICE) MACT Standard

Prepared for:
Coordinating Committee of the
Industrial Combustion Coordinated Rulemaking (ICCR)

Prepared by:
Reciprocating Internal Combustion Engine Work Group
Of the Industrial Combustion Coordinated Rulemaking

September 4, 1998

Table of Contents

I. Introduction

This paper documents the discussions that occurred within the Reciprocating Internal Combustion Engine (RICE) Work Group regarding a regulatory definition for "rich burn engines." Stationary RICE operate with various air-to-fuel ratios and, in general, may be classified as either rich or lean of stoichiometry. Stoichiometry is a precise point that may be defined as the chemically correct air-to-fuel ratio that would be required for complete combustion. Rich of stoichiometry refers to fuel-rich combustion, i.e., operation at any air-to-fuel ratio less than stoichiometry. Lean of stoichiometry refers to fuel-lean combustion, i.e., operation at any air-to-fuel ratio numerically higher than stoichiometry. All compression-ignition engines run lean of stoichiometry. Spark-ignition engines may run either rich or lean of stoichiometry, depending on engine design and setpoints for fuel flow and intake air.

The Work Group agreed by consensus that there should be a subcategory for Spark-Ignition, Natural Gas, 4-Stroke, Rich Burn engines (SI-NG-4SRB). However, the Work Group has not reached consensus on the appropriate regulatory definition for the RICE MACT standard to best distinguish engines in that subcategory from engines that would be included in the Spark-Ignition, Natural Gas, 4-Stroke, Lean Burn (SI-NG-4SLB) subcategory. The Work Group developed this paper to document the Work Group's discussions of this issue. The Work Group recommends that the Coordinating Committee forward the information presented in this paper to EPA as a recommendation so that EPA will consider the information in developing the regulatory definition of "rich burn engines" for the RICE MACT standard.

The need for a definition of rich burn in the context of the RICE MACT standard is discussed below, along with a list of the definitions discussed to date by the RICE Work Group. Sections II through VII provide a record of the definitions considered by the Work Group to date, the instances where these definitions have been used previously, and the Work Group views on the pros and cons of the use of the definitions for the RICE MACT standard.

The final section of this paper presents the Work Group's conclusions and recommendations to the Coordinating Committee regarding the definition of "rich burn engine".

A. Need for a Definition of "Rich Burn Engine" for the RICE MACT Standard

As indicated above, the need for a regulatory definition of "rich burn engine" arose out of the need to distinguish those engines that would be included in the SI-NG-4SRB subcategory from those engines that would be included in the SI-NG-4SLB subcategory for the RICE MACT standard.

For existing engines, the RICE Work Group identified ten subcategories:

- Spark-Ignition, Natural Gas 4-Stroke Rich Burn Engines
- Spark-Ignition, Natural Gas 4-Stroke Lean Burn Engines
- Spark-Ignition, Natural Gas 2-Stroke Lean Burn Engines
- Spark-Ignition, Digester Gas and Landfill Gas Engines
- Spark-Ignition, Propane, Liquid Petroleum Gas (LPG), and Process Gas Engines
- Spark-Ignition, Gasoline Engines
- Compression-Ignition, Liquid Fuel Engines (diesel, residual/crude oil, kerosene/naphtha)
- Compression-Ignition, Dual Fuel Engines
- Emergency Power Units
- Small Engines (200 brake horsepower or less)

Engines included in the Emergency Power Units subcategory were identified by the engine's use on an emergency basis. Engines in the Small Engines subcategory were identified by size (engines 200 brake horsepower or less). For engines that were not considered emergency power units or small engines, the RICE Work Group subcategorized the engines by whether the engines were spark-ignited or compression-ignited and by fuel type. For natural gas, the Work Group also subcategorized engines based on whether the engines were 2-stroke and 4-stroke engines and whether the engines were lean burn engines or rich burn engines.

The natural gas-fired engines were subcategorized further than engines using fuels other than natural gas for the following reasons:

- To reflect the engineering differences between 2-stroke and 4-stroke, rich-burn and lean-burn engines, and
- To reflect the fact that there are two most prevalent control devices in the existing population of engines that involve oxidation -- a 3-way catalyst, known as non-selective catalytic reduction (NSCR), and oxidation catalysts -- NSCR is mostly used on "rich burn engines" and oxidation catalysts are mostly used on "lean burn" engines for criteria pollutant control. [1]

Therefore, the RICE Work Group concluded that it was necessary to further subcategorize natural gas-fired engines. For the MACT floor analysis, 4-stroke natural gas-fired engines included in the ICCR Population Database were designated as SI-NG-4SLB or SI-NG-4SRB based on the manufacturer's designation of the engine model as a "rich burn engine" or a "lean burn engine." As a result of this analysis, the Work Group determined that the MACT floor for SI-NG-4SRB engines should be based on NSCR. For engines in all subcategories other than SI-NG-4SRB, the Work Group concluded that no MACT floor could be identified and therefore there was no MACT floor for those subcategories.

The Work Group presented its recommendations on subcategories and MACT floors to the ICCR Coordinating Committee at the July 1998 meeting. The ICCR Coordinating Committee agreed with the findings of the RICE Work Group regarding subcategories and MACT floor and on August 12, 1998, the Committee forwarded the “Recommended Subcategories and MACT Floors for Existing Stationary Reciprocating Internal Combustion Engines (RICE),” (MACT Floor Rationale) to EPA. The MACT Floor Rationale recommended to EPA that the MACT floor for SI-NG-4SRB engines should be based on the use of NSCR control technology. For engines in all other subcategories, MACT Floor Rationale recommended that there is no MACT floor.

[1] Based on a review of available information, the Work Group had determined that add-on control devices that involve oxidation are most applicable for HAPs reduction from RICE. NSCR is a 3-way catalyst system that simultaneously controls nitrogen oxides (NOx), carbon monoxide (CO), and hydrocarbons (HC). With regards to NSCR, the Work Group concluded that NSCR catalysts do involve oxidation and would exhibit some effectiveness in oxidizing formaldehyde and other similar HAPs.

Although the designation of an engine as "rich burn" by the manufacturer was used to analyze data in the ICCR Population Database to determine the MACT floor, the MACT Floor Rationale forwarded to EPA by the Coordinating Committee does not include a definition for the SI-NG-4SRB subcategory or for "rich burn engines." In Section 1.1.2.3 of the MACT Floor Rationale, it is noted that a common method used to distinguish between “rich burn” and “lean burn” engines is the percentage oxygen in the exhaust stream. The Rationale also indicates that several regulatory agencies have adopted a value of 4 percent oxygen in the exhaust as the defining limit for “rich burn” engines. The RICE Work Group has agreed that the information in Section 1.1.2.3 does not constitute a definition of “rich burn engines” for the RICE MACT standard. Rather, the facts were included as information to describe some of the current practices.

Since the July 1998 Coordinating Committee, the RICE Work Group has held a number of discussions regarding the appropriate approach to establish a regulatory definition of “rich burn engine” for the purposes of the RICE MACT standard. Some of the RICE Work Group members believe that the regulatory definition of "rich burn engines" should be based on technical characteristics of the engine. The Work Group members have not agreed on the specific technical characteristics that should be used to define "rich burn engines." Possible technical characteristics that have been discussed for the definition of "rich burn engines" include air-to-fuel ratio, lambda (air-to-fuel ratio divided by stoichiometric air-to-fuel ratio), exhaust oxygen content, and the manufacturer's designation of the engine as "rich burn." The Work Group members also have not agreed on the limits of the SI-NG-4SRB subcategory. Some Work Group members believed the subcategory should include only those engines that can use NSCR as a 3-way catalyst for the simultaneous reduction of NOx, CO, and HC. Other Work Group members believed that "rich burn engines" should include engines beyond those that may use NSCR as a 3-way catalyst, so long as all "rich burn engines" could meet the MACT requirements for the SI-NG-4SRB subcategory through the use of any device, such as an oxidation catalyst or an NSCR used solely for oxidation.

The possible definitions discussed to date are listed in the following section.

B. Definitions of Rich Burn Discussed by the RICE Work Group

The RICE Work Group has discussed the following definitions of “rich burn engine”:

- "Rich burn means engines that are designated as ‘rich-burn’ by the manufacturer based on the design of the engine model when manufactured.”
- "Rich burn means engines that can use non-selective catalytic reduction control technology.”
- "Rich burn means an engine with an air-to-fuel ratio (A/F) operating range that is near to stoichiometric or fuel-rich of stoichiometric and can be adjusted to operate with an exhaust oxygen concentration of 1 percent or less."
- "Rich burn engine means a two stroke or four-stroke spark-ignited engine where the manufacturer’s original recommended operating air/fuel ratio divided by the stoichiometric air/fuel ratio is less than or equal to 1.1.”
- "Rich burn engine means a two stroke or four-stroke spark-ignited engine where the operating air/fuel ratio divided by the stoichiometric air/fuel ratio is less than or equal to 1.1.”
- "Rich burn means a four-stroke, spark-ignited engine where the oxygen content in the exhaust stream before any dilution is 4% or less measured on a dry basis."
- "Rich burn means a four-stroke, spark-ignited engine where the oxygen content in the exhaust stream before any dilution is 1% or less measured on a dry basis."

Discussion of these definitions is provided below.

II. Define As Engines Designated Rich Burn By The Manufacturer

Definition Discussed by the Work Group:

> "Rich burn means engines that are designated as ‘rich-burn’ by the manufacturer based on the design of the engine model when manufactured.”

Pros:

- Definition is consistent with the methodology used to designate engines as “rich burn” in the ICCR Population Database. The engines designated as “rich burn” were used to determine the MACT floor for the SI-NG-4SRB subcategory.

- Since the definition relies on the manufacturer's original designation of the engine as a rich burn, owners or operators do not have the opportunity to adjust the engine to lean-burn status to avoid rich-burn regulatory requirements.

  [Note: For NOx, regulators were very concerned about this possibility since there were higher NOx emission limitations for lean-burn engines, which relied on different control technologies to reduce NOx. For the RICE MACT standard, similar oxidation control technologies have been identified for both rich burn and lean burn engines. However, it is unclear whether the MACT standard for SI-NG-4SRB engines will be the same or nearly the same as the MACT standard for SI-NG-4SLB engines.]

<u>Cons:</u>

- The definition of “rich burn engine” would be based solely on the manufacturer designation and there is not a definite cutpoint for rich burn that has been used consistently for all engine manufacturers. However, since engines with air/fuel ratios of around 16:1 are designated "rich burn" by manufacturers and engines with air/fuel ratios no less than 24:1 are designated "lean-burn," this should not be a significant problem.
- The definition relies on the designation specified by the manufacturer at the time of manufacture. The definition does not accommodate the re-manufacture and re-construction of existing engines which may result in conversions of engines originally specified as “rich burn” to operate significantly lean of stoichiometric conditions. The modified engines may have engineering and operating characteristics more closely akin to lean burn engines than to rich burn engines.
- Many rich-burn engines operate slightly lean of stoichiometric conditions. For those engines, the exhaust oxygen concentration may be higher than the level required to use NSCR controls as intended for NOx control. In order to use NSCR as intended for NOx control, it would be necessary to adjust the engine to run at 1 percent oxygen or less. However, engines may be able to use other devices to comply with MACT.
- In most cases, operators who install NSCR use an air-to-fuel ratio controller to maintain the proper air-to-fuel ratio and exhaust gas oxygen content required to use NSCR technology as intended for NOx control. However, for some older models of engines, commercially available air-to-fuel ratio controllers cannot ensure that the engines will operate with exhaust concentrations of 1 percent oxygen or less, at all load conditions, including low-loads.

<u>Instances Where the Definition Has Been Used Previously:</u>

- NONE

III. Define as Engines that Can Use Non-Selective Catalytic Reduction

Definition Discussed by the Work Group:

> "Rich burn means engines that can use non-selective catalytic reduction control technology."

Pros:

- Limits "rich burn engines" to only those engines that can use NSCR. With this definition, NSCR would be achievable for all engines in the subcategory.

Cons:

- The definition of "rich burn engine" would be based solely on a control technology, not the engineering characteristics of the engine.
- "Can use NSCR" is not a precise, measurable characteristic. To be covered under this definition, an engine must be able to be operated with NSCR as intended for NOx control. To avoid being covered under this definition, source owners and operators would need to demonstrate to permitting/ enforcement personnel that the engine cannot be operated with NSCR. [Note: In the latter case, the engine would be covered under requirements for lean burn engines.]

Instances Where the Definition Has Been Used Previously:

- NONE

IV. Define as Engines Near to Stoichiometric or Fuel-Rich of Stoichiometric

Definition Discussed by the Work Group:

> "Rich burn means an engine with an air-to-fuel ratio (A/F) operating range that is near to stoichiometric or fuel-rich of stoichiometric and can be adjusted to operate with an exhaust oxygen concentration of 1 percent or less."

Pros:

- Fuel-rich of stoichiometric is a precise, measurable point.
- Limits "rich burn engines" to only those engines that can be adjusted to operate with an exhaust oxygen concentration that is compatible with the use of NSCR as intended for NOx control. With this definition, NSCR would function as intended for NOx control on all "rich burn engines".
- Definition reflects the operating conditions of the engine, not simply the conditions specified by the manufacturer. Therefore, the definition accommodates diverse operating conditions of existing engines, which may result in higher exhaust oxygen content than the levels specified by the design of the engine manufacturer.

- Definition takes into account the possible re-manufacture or re-construction of an existing engine, which may result in an exhaust gas oxygen content different than that specified by the manufacturer.

<u>Cons:</u>

- Near to stoichiometric is not a precise, measurable point. Under this definition, for engines operating fuel-lean of stoichiometric, it would be necessary for source owners and operators to demonstrate to permitting/enforcement personnel that the engine could not be operated with an exhaust oxygen concentration of 1 percent or less.
- Since near to stoichiometric is not a precise point, it is unclear whether engines operating slightly lean of stoichiometric are included. Engine manufacturers do include engines slightly lean of stoichiometric as "rich burn."
- To determine whether an engine is covered under this definition, it is necessary to know the stoichiometric air-to-fuel ratio for the fuel being used, along with the operating air-to-fuel ratio. To determine operating air-to-fuel ratio, engine operators need to measure at least the oxygen content of the exhaust.
- The definition relies on air-to-fuel ratio, which is difficult to precisely measure in the field.

<u>Instances Where the Definition Has Been Used Previously:</u>

- The EPA Alternative Control Techniques Document for Nitrogen Oxide Emissions from Stationary Reciprocating Internal Combustion Engines uses this definition:

  “A rich-burn engine is classified as one with an air-to-fuel ratio (A/F) operating range that is near stoichiometric or fuel-rich of stoichiometric and can be adjusted to operate with an exhaust oxygen concentration of 1 percent or less."

V. Define as Engines where the Air-to-Fuel Ratio Divided by Stoichiometric Air-to-Fuel Ratio (Lambda) is 1.1 or Less

Definition Discussed by the Work Group:

"Rich burn engine means a two stroke or four-stroke spark-ignited engine where the manufacturer’s original recommended operating air/fuel ratio divided by the stoichiometric air/fuel ratio is less than or equal to 1.1.”

and

"Rich burn engine means a two stroke or four-stroke spark-ignited engine where the operating air/fuel ratio divided by the stoichiometric air/fuel ratio is less than or equal to 1.1.”

Pros:

- A lambda target, such as 1.1, is independent of fuel, whereas air-to-fuel ratio alone would be fuel dependent.
- Lambda 1.1 is a technically precise point, making compliance determinations definitive.
- If the definition relies on the manufacturer's original recommended air-to-fuel ratio, owners or operators do not have the opportunity to adjust the engine to lean-burn status to avoid rich burn regulatory requirements.
- To determine operating air-to-fuel ratio, engine operators can measure the oxygen content of the exhaust.

Cons:

- Lambda is more difficult to measure/calculate than exhaust oxygen levels. Two air-to-fuel ratios are necessary to determine lambda: the stoichiometric air-to-fuel ratio and either the manufacturer's recommended air-to-fuel ratio or the operating air-to-fuel ratio. The manufacturer's recommended air-to-fuel ratio may be difficult to determine for older engines. Where fuel composition changes significantly, the stoichiometric air-to-fuel ratio may be difficult to determine, since it is dependent on fuel composition. The operating air-to-fuel ratio is difficult to precisely measure in the field.
- If the definition relies on the air-to-fuel ratio originally specified by the engine manufacturer, the definition does not accommodate the diverse operating conditions of existing engines and the re-manufacture and re-construction of existing engines which may result in different air-to-fuel ratios than those specified by the design of the engine manufacturer.
- If the definition relies on lambda calculated with the current operating air-to-fuel ratio (not the manufacturer's specifications), owners and operators would have the opportunity to adjust the air-to-fuel ratio to raise lambda and thereby qualify the engine as a "lean burn engine." The definition does not incorporate sufficient constraints to prohibit engine owners and operators from temporarily adjusting the engine to avoid rich burn regulatory requirements.

  [Note: For NOx, regulators were very concerned about this possibility since there were higher NOx emission limitations for lean-burn engines, which relied on different control technologies to reduce NOx. For the RICE MACT standard, similar oxidation control technologies have been identified for both rich burn and lean burn engines. However, it is unclear whether the MACT standard for SI-NG-4SRB engines will be the same or nearly the same as the MACT standard for SI-NG-4SLB engines.]
- A lambda of 1.1 corresponds to approximately 2 percent oxygen in the exhaust. An exhaust concentration of 2 percent would not be compatible with the use of NSCR controls as intended for NOx control. In order to use NSCR as intended for NOx control, it would be necessary to adjust the engine to run at 1 percent oxygen or less. However, engines may be able to use other devices to comply with MACT.

- According to some Work Group members, NSCR may not be achievable for all engines in the rich burn subcategory if this definition were adopted. In order to use NSCR as intended for NOx control, it would be necessary to adjust the engine to run at 1 percent oxygen or less. However, for some older models of engines, commercially available air-to-fuel ratio controllers cannot ensure that the engines will operate with exhaust concentrations of 1 percent oxygen or less, at all load conditions, including low-loads. However, engines may be able to use other devices to comply with MACT.

<u>Instances Where the Definition Has Been Used Previously:</u>

- California's Ventura County and Sacramento Air Quality Management Districts, Rules 74.9 and 412, define rich burn engine as follows:

  "A two-stroke or four-stroke spark-ignited engine where the manufacturers original recommended operating air/fuel ratio divided by the stoichiometric air/fuel ratio is less than or equal to 1.1.

VI. Define as Engines with 4 Percent or Less Excess Oxygen in the Exhaust

Definition Discussed by the Work Group:

> "Rich burn means a four-stroke, spark-ignited engine where the oxygen content in the exhaust stream before any dilution is 4% or less measured on a dry basis."

<u>Pros:</u>

- Oxygen content of the exhaust is easy to measure on-site and determine whether an engine meets the criteria of 4 percent or less.
- Definition reflects the operating conditions of the engine, not simply the conditions specified by the manufacturer. Therefore, the definition accommodates diverse operating conditions of existing engines that may result in an exhaust gas oxygen content different than that specified by the manufacturer.
- Definition takes into account the possible re-manufacture or re-construction of existing engines, which may result in an exhaust gas oxygen content different than that specified by the manufacturer.
- Definition is used by some engine manufacturers.
- Since the exhaust oxygen limit is set fairly high, it would be difficult for engine owners and operators to adjust the air-to-fuel ratio sufficiently to raise the oxygen level in the exhaust and thereby qualify the engine as a "lean burn engine."

<u>Cons:</u>

- Definition is significantly to the lean side of stoichiometry.

- If the definition relies on exhaust concentration based on the current operating air-to-fuel ratio (not the manufacturer's specifications), owners and operators would have the opportunity to adjust the air-to-fuel ratio to raise the oxygen content and thereby qualify the engine as a "lean burn engine." The definition does not incorporate sufficient constraints to prohibit engine owners and operators from temporarily adjusting the engine to avoid rich burn regulatory requirements.

  [Note: For NOx, regulators were very concerned about this possibility since there were higher NOx emission limitations for lean-burn engines, which relied on different control technologies to reduce NOx. For the RICE MACT standard, similar oxidation control technologies have been identified for both rich burn and lean burn engines. However, it is unclear whether the MACT standard for SI-NG-4SRB engines will be the same or nearly the same as the MACT standard for SI-NG-4SLB engines.]

- An exhaust concentration of 4 percent is not compatible with the use of NSCR as intended for NOx control. In order to use NSCR as intended for NOx control, it would be necessary to adjust the engine to run at 1 percent oxygen or less. However, engines may be able to use other devices to comply with MACT.

- According to some Work Group members, NSCR as intended for NOx control would not be achievable for all engines in the rich burn subcategory if this definition were adopted. In order to use NSCR as intended for NOx control, it would be necessary to adjust the engine to run at 1 percent oxygen or less. However, for some older models of engines, commercially available air-to-fuel ratio controllers cannot ensure that the engines will operate with exhaust concentrations of 1 percent oxygen or less, at all load conditions, including low-loads. However, engines may be able to use other devices to comply with MACT.

<u>Instances Where the Definition Has Been Used Previously:</u>

- EPA AP-42 Emission Factors for Reciprocating Internal Combustion Engines uses this definition.

- Texas environmental regulations, Chapter 106, Exemptions from Permitting, 106.512, defines "rich burn engine" as "a gas-fired spark-ignited engine that is operated with an exhaust oxygen content less than 4.0% by volume." [Note: The definition in Texas's Chapter 117, Control of Air Pollution from Nitrogen Oxides, defines "rich burn engine" as a spark-ignited, Otto cycle, four-stroke, naturally aspirated or turbocharged engine that is capable of being operated with an exhaust stream oxygen concentration equal to or less than 0.5% by volume, as originally designed by the manufacturer."]

- California's Bay Area Air Quality Management District Rules and Regulations, BAAWMD Regulation 9-8-205 defines rich burn engine as follows:

  "Any spark or compression ignited internal combustion engine that is designed to be operated with an exhaust stream oxygen concentration of less than 4 percent, by volume. The exhaust gas oxygen content shall be determined from the uncontrolled exhaust stream."

- California's South Coast Air Quality Management District Rule 1110.1, includes the following definition:

  "A rich-burn engine is an Otto cycle engine that can be adjusted to run with an exhaust stream oxygen concentration of less than 4 percent by volume."

- California's Santa Barbara County APCD Rule 333 defines "rich burn engine" as an engine with 4 percent oxygen in the exhaust, but also limits engines already permitted as "rich burn engines" from changing their designation after the date of rule adoption:

  "Rich-burn engine means a spark-ignited, Otto cycle, or four-stroke naturally aspirated engine that is operated with an exhaust stream oxygen concentration of less than 4 percent by volume. The exhaust gas oxygen content shall be determined from the uncontrolled exhaust stream. Additionally, any engine which is designated as a rich-burn engine on a District Permit on the date of rule adoption shall be a rich-burn engine."

VII. Define as Engines with 1 Percent or Less Excess Oxygen in the Exhaust

Definition Discussed by the Work Group:

> "Rich burn means a four-stroke, spark-ignited engine where the oxygen content in the exhaust stream before any dilution is 1% or less measured on a dry basis."

<u>Pros:</u>

- Oxygen content of the exhaust is easy to measure on-site and determine whether an engine meets the criteria of 1 percent or less.
- The definition is consistent with the use of NSCR as intended for NOx control, which requires that oxygen be 1 percent or less. With this definition, the use of NSCR as intended for NOx control would be achievable for all rich burn engines.
- Definition reflects the operating conditions of the engine, not simply the conditions specified by the manufacturer. Therefore, the definition accommodates diverse operating conditions of existing engines, which may result in an exhaust gas oxygen content different than that specified by the manufacturer.
- Definition takes into account the possible re-manufacture or re-construction of existing engines, which may result in an exhaust gas oxygen content different than that specified by the manufacturer.

<u>Cons:</u>

- If the definition relies on exhaust oxygen content based on current operating air-to-fuel ratio (not the manufacturer's specifications), engine owners and operators would have the opportunity to adjust the air-to-fuel ratio to raise the oxygen level in the exhaust and thereby qualify the engine as a "lean burn engine." The definition does not incorporate sufficient constraints to prohibit engine owners and operators from temporarily adjusting the engine to avoid rich burn regulatory requirements.

  [Note: For NOx, regulators were very concerned about this possibility since there were higher NOx emission limitations for lean-burn engines, which relied on different control technologies to reduce NOx. For the RICE MACT standard, similar oxidation control technologies have been identified for both rich burn and lean burn engines. However, it is unclear whether the MACT standard for SI-NG-4SRB engines will be the same or nearly the same as the MACT standard for SI-NG-4SLB engines.]

- While this definition limits rich burn engines to those engines with 1 percent or less exhaust oxygen content, some engine manufacturers use a definition of 4 percent exhaust gas oxygen content.

- The definition limits "rich burn engines" to those engines that may use NSCR as intended for NOx control. However, it is unclear whether this is important for the RICE MACT, because the RICE MACT may permit the use of alternate controls that are consistent with other definitions.

<u>Instances Where the Definition Has Been Used Previously:</u>

- Massachusetts regulations, Title 310, Chapter 7. Air Pollution Control, defines "rich burn engine" as "any stationary reciprocating internal combustion engine that is not a lean burn engine." "Lean burn engine" is defined as "a stationary reciprocating internal combustion engine in which the amount of O2 in the engine exhaust gases is 1.0% or more."

- Ohio environmental regulations (OAC 3745-14-01(B)(30), Effective 6/21/94) and Rhode Island (Subsection 27.1.23 of Air Pollution Control Regulation No. 27, Amended 1/16/96) use similar definitions:

  "Rich burn engine means an internal combustion engine where the amount of oxygen in the engine exhaust gases is less than one percent, by weight."

- New York environmental regulations, 6 NYCRR 227-2.2(b)(15), Filed 1/19/94, define "rich burn internal combustion engine" as "any stationary internal combustion engine that is not a lean burn engine as described in paragraph (8) of this subdivision." Paragraph 8 defines "lean burn internal combustion engine" as "any stationary internal combustion engine that is operated so that the amount of oxygen in the exhaust is 1.0 percent or more, by volume."

- North Carolina environmental regulations, Administrative Code 15A, Chapter 2d, Section 1401(15), Effective 4/1/95, define 1 percent as the break-point for rich burn/lean burn, but limit the definition to engines designed and manufactured for 1 percent exhaust oxygen:

"Rich-burn internal combustion engine means a spark ignition internal combustion engine originally designed and manufactured to operate with an exhaust oxygen concentration less than or equal to one percent."

- New Hampshire environmental regulations (NHAR-Env-A 1211.01(an), Effective 5/20/94) have a similar, but not identical regulation. In this case, "rich burn engine" is defined as "any stationary internal combustion engine that is not a lean burn engine." A "lean burn engine" is defined as "a stationary, internal combustion engine in which the amount of O2 in the engine exhaust gases is 1.0% or more, by weight, unless otherwise specified by the engine manufacturer."

VIII. Conclusions and Recommendations

Engines operating rich of the stoichiometric air-to-fuel ratio are clearly rich burn engines. Technically, when engines operate lean of stoichiometric (stoichiometric correlates to approximately 0.5% oxygen), they are no longer operating in a rich-burn mode. However, according to engine manufacturers, academics, and air regulations developed for NOx control, engines operating slightly lean of stoichiometric are considered "rich burn engines." Air regulatory definitions of "rich burn engines" have included engines operating up to 1 percent oxygen, up to 4 percent oxygen, and up to a lambda of 1.1. In addition, recognizing that engines are adjustable, some regulators have tied the definition of "rich burn engines" to manufacturers' recommended air-to-fuel ratio or exhaust oxygen content to limit the opportunity for source owners and operators to adjust the engine so that it is no longer considered a "rich burn."

From the standpoint of the RICE MACT, it is necessary that the standard be achievable for all engines in each subcategory. For SI-NG-4SRB engines, the RICE Work Group has identified NSCR as the MACT floor. There may be control options for SI-NG-4SRB engines other than NSCR.

Based on the information presented in this paper and the discussions of the RICE Work Group, it is clear that the definition of rich burn engines for the RICE MACT standard is complicated. At this time, the RICE Work Group has not reached consensus on a regulatory definition of “rich burn engine” for the purposes of the MACT standard. The Work Group views at this time may be summarized as follows:

- With regards to the technical characteristics that should be used to define "rich burn engines," some Work Group members believe that exhaust oxygen content should be the basis for the definition of "rich burn engines" because it is easily determined in a precise manner in the field and it provides an indication of the engine's air-to-fuel ratio. Other Work Group members believe that lambda 1.1 should be the basis for the definition of "rich burn engines" because it is independent of fuel, is a technically precise point, and makes compliance determinations definitive.

- With regards to the limits of the definition of "rich burn engines," some Work Group members believe that "rich burn engines" should include only those engines that can use NSCR as a 3-way catalyst for the simultaneous control of NOx, CO, and HC. Other Work Group members believe that "rich burn engines" should include engines beyond those that may use NSCR as a 3-way catalyst, so long as all engines included in the SI-NG-4SRB subcategory could meet the MACT requirements through the use of any device, such as an oxidation catalyst or NSCR used solely for oxidation.

- In order to prevent engine owners/operators from adjusting the operating conditions to avoid rich burn regulatory requirements, some Work Group members believe it is important to link the definition of "rich burn engines" to the manufacturer's specifications for air-to-fuel ratio or exhaust oxygen content or to include other constraints to limit the temporary adjustment of the engine to avoid rich burn regulatory requirements. Other Work Group members believe it is important that the definition of "rich burn engines" not rely solely on the manufacturer's specifications. These Work Group members believe the definition should take into account the possible re-manufacture or re-construction of an existing engine, which may result in engineering and operating characteristics more closely akin to lean burn engines than to rich burn engines. In addition, these Work Group members believe the definition should accommodate diverse operating conditions, which may result in an exhaust gas oxygen content different than that specified by the manufacturer.

The RICE Work Group agrees that the definition for “rich burn engine” should accomplish the following goals:

- The definition should incorporate engines that operate both fuel-rich and slightly lean of stoichiometry.
- The definition should incorporate other engines only where the control needed to meet the MACT regulation is achievable.

- The definition should recognize that existing engines, originally considered "rich-burn," might have been modified in the field to run at conditions that are significantly lean of stoichiometry.
- The definition should not allow engine owners and operators the opportunity to adjust the engine to lean burn status to avoid rich burn regulatory requirements.